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Legumes for improving maize yields and income in semi-arid Kenya

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Abstract

An experiment was conducted at the research station of the International Centre for Research in Agroforestry (ICRAF) at Machakos, Kenya from November 1989 to February 1996 to evaluate the effect of annual and perennial legumes on soil fertility, cereal yields and economic returns. The study evaluated six cropping systems: (1) continuous sole maize, (2) maize rotated with short-duration legume, cowpea (*Vigna unguiculata* L. Walp.), (3) maize rotated with long-duration legume, pigeonpea (*Cajanus cajan* L. Millsp.), (4) maize intercropped with pigeonpea, (5) hedgerow intercropping of maize and a perennial legume, gliricidia (*Gliricidia sepium*), and (6) continuous sole maize, green-manured with gliricidia prunings produced from an equivalent area outside the cropped field ('biomass transfer technology'). Maize–cowpea sequential and pigeonpea/maize intercropping systems produced, respectively, 17 and 24% higher maize yields than continuous sole maize, but maize–pigeonpea rotation yielded only marginally better. Hedgerow intercropping did not increase maize yields because increased yields during the few high rainfall seasons did not compensate the yield losses in other seasons due to the competition of hedgerows for water with crop. Green manuring with gliricidia prunings increased maize production by 27%, but this technology was not economical because of high labour costs for production and application of prunings to the crop. The annual grain legume-based cropping systems were 32–49% more profitable than continuous sole maize, making them attractive to small farmers in semi-arid tropics. Both cowpea and pigeonpea were affected by pests and diseases, which indicated the need for integrated pest management for realising the potential benefits of these legume-based systems.

Keywords: Cowpea; Gliricidia; Hedgerow intercropping; Legumes; Maize; Pigeonpea; Semi-arid tropics; Soil fertility; Kenya

1. Introduction

In sub-humid and semi-arid tropical Africa having settled agriculture and high population density, long periods of following are no longer practiced and land is cropped continuously after clearing. It is common for food crop yields to decline over years because of nutrient depletion, as these crops are rarely fertilized in smallholder farms. Consequently, yields of cereals often do not exceed 1 t ha^{-1}, and legumes 0.5 t ha^{-1} per crop season (Tiffen et al., 1994). Fertilizer use is low because of their unavailability at the right time, high cost, and risks from erratic and limited rainfall. It is therefore a major challenge to sustain crop yields and economic returns in low input agricultural systems.

The use of different food, herbaceous (green- manure) and forage legumes in cropping systems, either as intercrops or in rotations with other crops, for improving soil fertility is a well-known practice in the tropics. Herbaceous legumes that serve the single purpose of improving soil fertility, however, have not been widely adopted by small farmers because they

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cannot afford to grow them at the expense of food crops on their limited land holdings. Dual-purpose legumes that produce food and feed [e.g. cowpea (*Vigna unguiculata* L. Walp.); groundnut (*Arachis hypogea* L.); pigeonpea (*Cajanus cajan* L. Millsp.] and forage legumes (e.g. *Stylosanthes* spp., *Trifolium* spp. *Vicia* spp.) are attractive particularly to small-scale farmers who practice mixed crop/livestock systems. Besides generating cash income to farmers through sale of grain and/or livestock products (milk, meat, manure), these legumes increase the yields of subsequent cereal crops grown in rotation by improving the soil chemical, physical and biological properties (Haque et al., 1995). However, forage legumes have not been adopted by farmers in the semi-arid east Africa (P. Wandera, Kenya Agricultural Research Institute, Katumani, pers. commun.).

Food legumes such as cowpea, guar (*Cyamopsis tetragonoloba*), mung bean (*Vigna aureus* L.), moth bean (*Phaseolus aconitifolia*), pigeonpea and groundnut, and fodder legumes such as berseem (*Trifolium alexandrinum*) were found to increase yields of subsequent cereal crops in semi-arid India by an equivalent effect of 30–40 kg N ha^{-1} (Lal et al., 1978; Kumar Rao et al., 1983). Nitrogen (N) contribution by legumes to other crops in the system depends on the species, biological N_2 fixation and the growth of legumes as determined by climate and soil, and management of residues. Grain legumes contribute less nitrogen than herbaceous legumes to subsequent crops in rotation (Giller et al., 1997), because most of the N fixed biologically by grain legumes is translocated to grain and both the grain and the residues are invariably removed from fields for human and livestock use. Hence, the N requirement of cereal crops can seldom be met from the residual effects of grain legumes, particularly in favourable seasons. Additional N from fertilizers and/or other organic sources is required to exploit the potential of such seasons.

In semi-arid Kenya, maize (*Zea mays* L.) is commonly intercropped or rotated with bean (*Phaseolus vulgaris* L.), pigeonpea or cowpea, although the relative proportion of the legume in mixed systems is small. The N removed by maize in this region could be as much as 25 to 40 kg N ha^{-1} per season, which means that a matching amount of N needs to be supplied for long-term sustainability of production. Nitrogen fixation by bean is notoriously inconsistent, with or without inoculation, but cowpea nodulates well by the ubiquitous *Bradyrhizobium* sp. and fixes up to 200 kg N^{-1} (Pilbeam et al., 1995). Preliminary trials in the early eighties indicated higher maize yields in rotation with sole crops of legumes (cowpea and bean) than in intercropping with legumes or continuous sole maize (Nadar and Faught, 1984).

Perennial tree legumes may have greater scope to replenish soil fertility than annual grain legumes by their ability to exploit the residual water and subsoil nutrients that crops cannot utilize, withstand drought, and hence produce higher biomass. Their year-round growth may lead to higher biological N fixation (Dommergues, 1995; Giller et al., 1997). Other advantages of perennial legumes include an absence of recurring establishment costs, opportunity to grow crops simultaneously without sacrificing land (Kang et al., 1990) and improved soil physical conditions and higher water infiltration because of their root activity (Rao et al., 1998). If the species are palatable, some or all of the multiple harvests in a year can be fed to livestock to improve their productivity and manure recycled to the fields to maintain soil fertility (Kang et al., 1990; Mathuva et al., 1998). However, most tree legumes could be highly competitive with crops for growth resources if they are not managed properly (Rao et al., 1998). The competition from perennial legumes can be minimized by pruning them low and/or frequently, or by selecting species that produce coppice growth slowly (Duguma et al., 1988). Few studies compared the perennial legumes with annual legumes for soil fertility improvement and/or income generation in semi-arid climates. The objectives of the studies were to (1) evaluate if soil fertility and maize yields can be maintained or improved by integrating annual grain legumes in cropping systems, (2) examine whether perennial legumes have greater potential for improving soil fertility and crop yields than annual legumes in semi-arid climates and (3) determine which of the systems are more profitable for small-scale farmers.

2. Materials and methods

2.1. Experimental site

The experiment was conducted at ICRAF's Machakos Research Station (1°33′S and 37°14′E)

75 km southeast of Nairobi, Kenya, from November 1989 to February 1996. The site represents the drier end of the bimodal highlands of East Africa, with an elevation of 1560 m, 760 mm rainfall and a mean annual temperature of 19.2°C. Rainfall occurs in two seasons, the first, known as the ‘long rains’, receiving about 330 mm, from mid-March to the end of July, and the second, known as the ‘short rains’, receiving about 365 mm, from mid-October to mid-February. The soils are Kandic Rhodustalfs (Alfisols, USDA soil taxonomy), which are usually 1 to 2 m deep on hill crests but shallow on hill slopes. The 0–15 cm soil layer of the experimental site was sandy clay loam in texture (32% clay and 54% sand) with pH (1 : 2.5 w/v water) = 6.4, organic carbon (acid-dichromate oxidation at 150°C) = 1.3%, bicarbonate-EDTA extractable P = 16 mg kg^{-1}, exchangeable Ca = 6.8 $cmol_c\ kg^{-1}$, exchangeable Mg = 2.2 $cmol_c\ kg^{-1}$, and exchangeable K = 0.75 $cmol_c\ kg^{-1}$. The experimental site was grazed heavily by the cattle of neighbouring farmers for many years. It was cleared of weeds and sparse bushes in October 1988 and cropped uniformly with maize in the 1988 short rains and finger millet (*Eleusine coracana* L. Gaertn.) in the 1989 long rains and the residues after harvest removed from the field.

2.2. Treatments

The study evaluated six cropping systems: (1) continuous double cropping of sole maize (MM), (2) cowpea–maize annual rotation (one crop in each season of a year, CM), (3) pigeonpea/cowpea intercrop-maize two-year rotation (pigeonpea/cowpea intercrop in one year and maize both seasons of the following year, P/CM), (4) continuous pigeonpea/maize annual intercropping (P/M), (5) hedgerow intercropping (synonymous with alley cropping) of gliricidia (*Gliricidia sepium* (Jacq.) Steud.) and maize (G/M) and (6) continuous double cropping of sole maize, green-manured with gliricidia prunings produced outside the cropped field on an equivalent area (MMG). Systems 2 and 3 were duplicated starting with maize to permit evaluation of legume effects every year without confounded with seasons. System 6 represents a ‘biomass transfer technology’ where biomass was produced on additional land. All treatments were evaluated in 9 m wide by 8 m long plots, replicated three times in a randomized complete block design.

2.3. Crop management

The land was cultivated by hand hoe at the beginning of each cropping season and crops were often sown in the dry soil just ahead of the rains. The recommended cultivars and populations were used for maize (cv. ‘Katumani composite’, crop cycle 125 days), cowpea (cv. ‘K 80’, crop cycle 100 days) and pigeonpea (cv. ‘ICP 13155’ or ‘Katumani 81/3/3’, both matured in 330 days). Pigeonpea was sown every year at the beginning of the short rains and harvested at the end of the long rains. Fig. 1 shows the spatial arrangements and populations of crops for sole and intercropping systems. The amount of gliricidia biomass applied to maize in MMG was estimated based on the biomass produced by the two middle rows and representing an equivalent maize area.

Gliricidia (accession 15/84, provenance Gualan, Gautamala) was established by transplanting 6-week-old seedlings raised in polybags. It was pruned for the first time 12 months after planting at the start of the 1990 short rains. Hedges were pruned back to 0.5 m height at the beginning of each cropping season and 5–6 weeks after planting maize, and the prunings incorporated in the soil. To avoid interference between agroforestry and annual crop plots through the lateral spread of gliricidia roots, 0.3 m wide and 1 m-deep trenches were dug, gliricidia roots severed and the trenches filled back, at the beginning of each season from the 1990 short rains. Root pruning was also done between gliricidia and maize in MMG (see Fig. 1).

No fertilizer was applied to crops throughout the study period to accord with farming practice. However, grain legumes were protected from major pests on a ‘minimum-protection’ basis, as many farmers do spray insecticides during flowering/podding, and to avoid confounding the potential soil fertility benefits of legumes with variable pest infestations. They were sprayed usually two times per season with Diazinon (a.i. diazinon) at 0.4 l ha^{-1}, Ambush (a.i. cypermethrin) at 1.0 l ha^{-1} or Dimethoate (a.i. dimethoate) at 0.5 l ha^{-1} to control aphid (*Aphis craccivora*) and pod borer (*Maruca testulalis*) on cowpea and pod borer (*Helicoverpa armigera*) and podfly (*Melanagromyza*

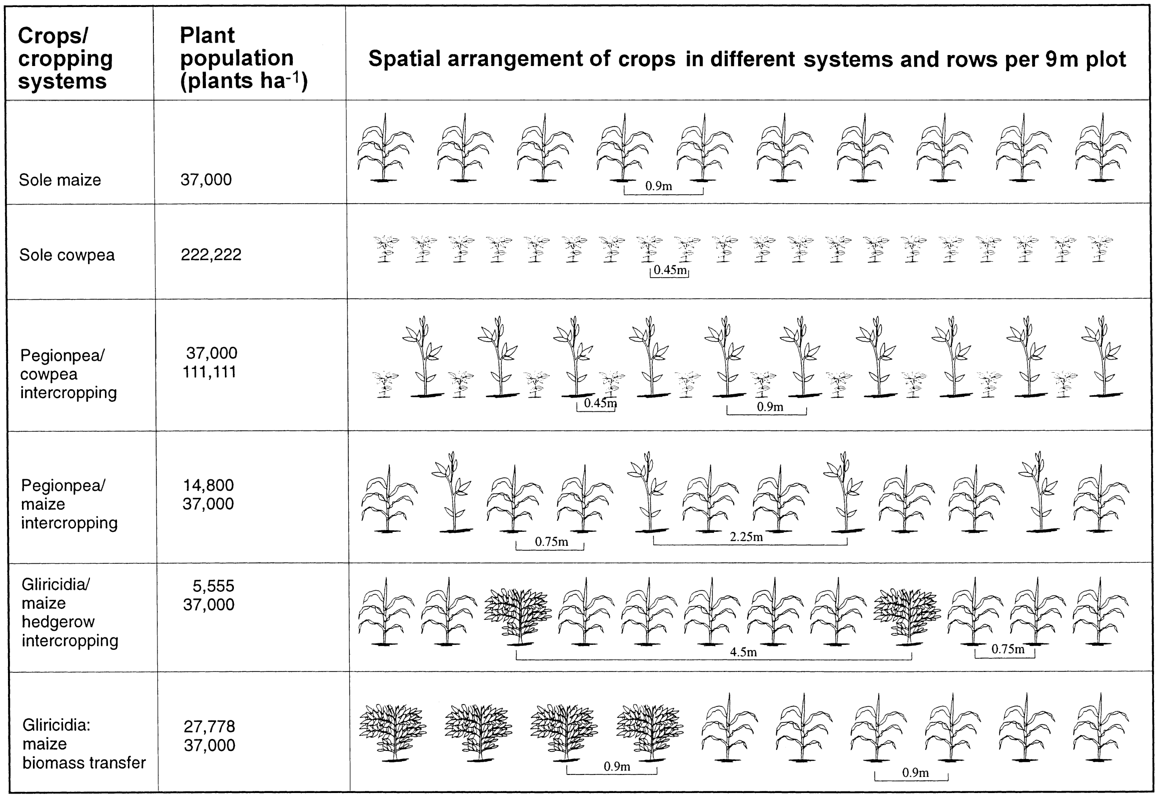

Fig. 1. Plant population, row spacing and row arrangement of crops in sole cropping, intercropping and biomass transfer systems.

chalcosoma) on pigeonpea. Although gliricidia was occasionally infested with aphid (*Aphis craccivora*), no insecticide was used to control it, as the pest did not affect the overall growth of trees. Both the annual legumes had suffered from wilt (*Fusarium udum*) over the years, but pigeonpea wilt was checked to some extent by replacing the cv. IC 13155 with a relatively more wilt-tolerant Katumani 81/3/3 from the 1992 short rains.

2.4. Data collection and analyses

A plot size of 27 m^2 was harvested for determining crop yields (grain, stover, haulms and stalks) in systems 1 to 5, leaving 1 m head-border on each ends and appropriate number of rows on both sides. In MMG, four maize rows of 6 m length were harvested, and yield per ha computed. Maize stover, cowpea haulms and pigeonpea stalks were removed from the plots typical of the farming practice and valued in economic analysis. The grain legumes shed most of their foliage by harvest, which was measured on two sample quadrats per plot (from 1992 long rains to 1994 long rains) and incorporated in the soil every season/year.

Soil samples were taken from 10 locations within each plot to 0–15 and 15–30 cm depths in October 1989 (at the start of the trial), March 1993 and August 1994. In MMG, soil samples were collected from the maize area only. The samples collected from each plot were composited, shade dried, crushed and sieved through a 2 mm mesh before being analyzed for major nutrients. Soil organic matter (SOM) pools and mineralisation rates of different pools were measured on samples collected in the 1993 long rains and reported by Barrios et al. (1996a, b). In the 1995 short rains, mineral nitrogen (NH_4-N + NO_3-N) of the 0–30 cm layer soil was measured at five different periods following the methods described by Anderson and Ingram (1993) to evaluate the N-supplying capacity of the soil in the different systems.

Table 1
Inputs and their costs, and values of crop products (US$) in different cropping systems

Item	Sole maize (per season)	Sole cowpea (per season)	Pigeonpea/cowpea (per year)		Pigeonpea/maize (per year)		Hedgerow intercropping (per season)	Sole maize green manured (per season)
			Pigeonpea	Cowpea	Pigeonpea	Maize		
Inputs								
Seed rate (kg ha^{-1})	25	30	9	15	4	19	25	25
Seed cost (US$ kg^{-1})	0.2	0.63	0.54	0.63	0.54	0.2	0.2	0.2
Tree seedlings (no. ha^{-1})	–	–	–	–	–	–	6100	30 550
Cost (US$ seedling^{-1})[a]	–	–	–	–	–	–	0.03	0.03
Pesticides (US$ ha^{-1})[b]	–	64 ± 39	107 ± 63	–	51 ± 38	–	–	–
Labour (workdays)[c]								
Land preparation	30	30	30	–	30	–	30	30
Sowing	12	20	12	10	6	12	12	12
Planting trees[d]	–	–	–	–	–	–	21	30
Pesticide application[d]	–	8 ± 3	15 ± 7	–	7 ± 2	–	–	–
Pruning and application[e]	–	–	–	–	–	–	12	45
Weeding	30	20	22	–	37	–	30	28(15)[f]
Harvesting and removal[g]	23 ± 5	17 ± 8	11 ± 7	10 ± 3	8 ± 2	27 ± 5	21 ± 9	24 ± 6
Threshing and transport[g]	23 ± 5	17 ± 8	17 ± 10	15 ± 5	13 ± 3	214	21 ± 9	276
Outputs								
Grain (US$ kg^{-1})	0.20	0.63	0.54	0.63	0.54	0.20	0.20	0.20
Stover (US$ kg^{-1})	0.03	–	–	–	–	0.03	0.03	0.03
Stalks (US$ kg^{-1})	–	–	0.03	0.03	–	–	–	–
Haulms (US$ kg^{-1})	–	0.08	0.08	0.08	0.08	–	–	–

[a] One-time cost of gliricidia seedlings for hedgerow intercropping and 1.0 ha of gliricidia biomass production plot for green manuring of maize; cost of an extra 10% seedlings was included for gap filling.
[b] Cost of insecticide sprays varied from season to season depending on the number of sprays and chemicals used. Values are means across seasons (or years) with standard deviation.
[c] Labour wage was US$ 1.66 per workday.
[d] Labour for plant protection depended on the number of sprays and the material used. Values are means across seasons (or years) with standard deviation.
[e] Dependent on biomass harvested at each pruning; hedgerows were pruned two times per season.
[f] Value in parentheses is labour for weeding of pure gliricidia block needed only in the planting season.
[g] Labour for harvesting, removal of stover from field, threshing and transport to homestead depended on crop growth and produce harvested. Values are means across seasons (or years) with standard deviation.

The effect of different legumes on soil fertility was evaluated by examining maize yields in each season and across seasons, and changes in nutrient status in the topsoil. Different systems were compared on the basis of financial analysis conducted, taking into account the costs of variable inputs (labour, seed, pesticides) and the value of all products (grain, stover or stalks, legume husk). Inputs and outputs were valued according to the market rates prevailing in November 1996, obtained through surveys in the area (Table 1). Labour for field operations was estimated based on observations in large production plots at the station and they were adjusted in different seasons for crop growth-dependent operations such as harvest, threshing, pruning hedgerows, etc. The values were discounted at 10% per crop season (20% per year) as appropriate for resource-poor, smallholder farmers. All monetary values were converted to US dollars at the rate of US$ 1.0 = KSh 55.7.

Economic performance of systems was evaluated on the basis of two indicators: net returns to land and returns to labour. Returns to land is the difference between discounted gross returns and discounted costs (including labour), which is a relevant parameter for households having land constraint. Returns to labour is the difference between discounted gross returns and

discounted non-labour costs divided by the number of labour days. This is a more appropriate measure for households with relatively low labour and those with ample off-farm employment, and can be directly compared with the wage rate. Sensitivity analysis was conducted by varying legume to maize price ratios (1 : 1 to 4 : 1), labour wage (100, 80, 60 and 40% of current minimum wage) and yields of grain legumes (100, 80, 60 and 40% of yields in the study), as a reflection of farmers investment on pest control. The data of the two economic indicators, calculated plot-wise, were also subjected to ANOVA as with other biological parameters.

3. Results

3.1. Maize yields

Maize yields in continuous sole cropping exceeded $2\,t\,ha^{-1}$ in all seasons except the 1991 long rains when rainfall was 29% less than normal and erratic, and the 1993 long rains when rains failed completely (Table 2). Maize following cowpea (averaged over the two cowpea-based rotations) produced significantly higher yields than continuous sole maize in three seasons and similar yields in nine seasons. The average maize yield per season after cowpea was significantly higher than continuous maize by 17% ($p < 0.01$). Maize subsequent to pigeonpea/cowpea intercrop (averaged over the two pigeonpea-based rotations) gave higher yields than continuous sole maize in two seasons, and similar yields in 10 seasons. The average yield per season of maize rotated with pigeonpea/cowpea intercrop was not significantly different from that of continuous sole maize. Maize intercropped with pigeonpea gave similar yields to sole maize in comparable seasons, but the average yield over all seasons was significantly higher ($p < 0.05$) than that of continuously sole-cropped maize, because there was no maize failure in intercropping in the 1993 long rains unlike the case in other systems.

Hedgerow intercropping produced lower maize yields than continuously sole-cropped maize in four seasons, similar yields in seven seasons and a higher yield in only one season (Table 2). The average yield per season from hedgerow instercropping was only 5% lower than that from continuous sole maize, and the two systems did not differ significantly. Maize (grown on 1 ha) green-manured with gliricidia prunings produced from an equivalent area outside the cropped field yielded significantly higher than maize control by 25–87% in five seasons, and they produced similar yields in seven other seasons. Averaged over

Table 2
Maize grain yield ($t\,ha^{-1}$) in legume-based cropping systems at Machakos, Kenya during November 1989-February 1996

Systems	1989–90		1990–91		1991–92		1992–93		1993–94		1994–95		1995	Yield per season
	SR[a]	LR[a]	SR	LR	SR	LR	SR	LR[b]	SR	LR	SR	LR	SR	
1. Maize–maize	3.02	2.18	2.95	1.41	3.19	2.91	3.40	0.0	2.95	2.10	2.92	2.80	2.14	2.46
2a. Cowpea–maize	–	2.41	–	1.91	–	2.19	–	0.0	–	2.20	–	4.45	–	2.89
2b. Maize–cowpea	3.50	–	3.01	–	3.28	–	4.81	–	2.55	–	4.52	–	2.58	–
3a. Pigeonpea/cowpea–maize	–	–	3.06	2.22	–	–	3.95	0.0	–	–	3.67	3.54	–	2.67
3b. Maize–pigeonpea/cowpea	2.93	2.00	–	–	3.40	3.11	–	–	2.35	2.25	–	–	2.13	–
4. Pigeonpea/maize	3.17	–	3.38	–	3.09	–	4.03	–	2.25	–	3.80	–	1.67	3.05
5. Gliricidia/maize	3.09	1.53	2.79	0.86	3.61	2.29	4.17	0.0	2.14	0.90	4.40	3.41	1.12	2.33
6. Maize–maize (green-manured)	3.11	2.22	3.68	2.44	3.34	3.02	5.02	0.0	2.78	2.32	5.48	5.10	2.00	3.12
SED[c]	0.46	0.29	0.31	0.27	0.41	0.38	0.54	–	0.41	0.14	0.42	0.52	0.24	0.18
Rainfall (mm)[d]	360	450	380	235	400	250	810	95	335	234	585	285	245	

[a] SR: short rains (mid-October to mid-February) LR: long rains (mid-March to July).
[b] Maize failed due to poor rainfall.
[c] SED: standard error of difference of treatment means.
[d] Seasonal rainfall from one week prior to sowing to the harvest of maize.

seasons, maize with gliricidia biomass transfer produced 27% higher yield than continuous sole maize ($p < 0.01$). If both maize and gliricidia were to be produced on 1 ha of land (as the other cropping systems), for example in 50 : 50 proportion, then maize yield from green-manured system would be only 65% of that from the control system. This means that maize production cannot be increased if green manure is to be produced in situ at the expense of crop area. Maize stover yields were similarly affected as the grain yields by different cropping systems (data not presented).

Maize yields (y) in continuous sole cropping were linearly related to rainfall (x) over the seasons ($y = 1.90 + 0.002x$, $r = 0.60$*) and yields in the green manure system were also similarly related to rainfall. Maize yields indicated stronger linear relationship with rainfall in intercropping with pigeonpea ($y = 1.29 + 0.004x$, $r = 86$**) and gliricidia hedgerows ($y = 0.49 + 0.005x$, $r = 0.73$**), where maize had to compete with the respective legumes for water. However, maize yields in rotation with grain legumes did not show a significant relationship with rainfall. This might be because legumes grown in rotation with maize modified soil water status through improved soil structure and higher rainfall infiltration.

3.2. Legume yields

Sole cowpea in rotation with maize produced on average slightly less than 1 t ha^{-1} of grain per year (0.92 t), whereas pigeonpea/cowpea intercrop in rotation with maize produced 0.55 t ha^{-1} of pigeonpea and 0.62 t ha^{-1} of cowpea, or 27% higher legume yield (Table 3). The pigeonpea/maize intercrop averaged 0.78 t ha^{-1} of pigeonpea grain per year. Pigeonpea intercropped with maize produced 2.3–3.7 t ha^{-1} of stalks but that intercropped with the less competitive cowpea and grown in rotation with maize yielded much higher stalk yields (3.1–6.7 t ha^{-1}). Both pigeonpea and cowpea had suffered from stand mortality over the years because of wilt. Pigeonpea experienced higher wilt in continuously grown maize/pigeonpea intercrop system than in maize–pigeonpea rotation. Whereas 15–25% of pigeonpea stand was affected by fusarium wilt in intercropping during 1992–1995, only 3–19% stand was affected by wilt in rotational system during that period. Although the wilt incidence on cowpea was lower in the earlier years, its occurrence

Table 3
Grain yields of legumes and prunings of gliricidia in different cropping systems at Machakos, Kenya

System	1989–90		1990–91		1991–92		1992–93		1993–94		1994–95		1995	Average per year (or per season)[b]
	SR[a]	LR[a]	SR	LR	SR	LR	SR	LR	SR	LR	SR	LR	SR	
Cowpea (t ha^{-1})														
2a Cowpea–maize	1.30	–	0.88	–	0.83	–	1.66	–	0.94	–	1.03	–	–	0.89
2b Maize–cowpea	–	0.42	–	1.00	–	1.61	–	0.00	–	0.69	–	0.23	–	
3a Pigeonpea/cowpea–maize	1.26	–	–	–	0.53	–	–	–	1.03	–	–	–	–	0.49
3b Maize–pigeonpea/cowpea	–	–	1.05	–	–	–	1.47	–	–	–	0.85	–	–	
SED	0.19	–	0.05	–	0.36	–	0.03	–	0.30	–	0.46	–	–	–
Pigeonpea (t ha^{-1})														
3a Pigeonpea/cowpea–maize	–	0.58	–	–	–	0.81	–	–	–	1.20	–	–	–	0.55
3b Maize–pigeonpea/cowpea	–	–	–	2.20	–	–	–	0.30	–	–	–	1.54	–	
4. Pigeonpea/maize	–	0.74	–	0.95	–	0.77		0.86		0.60		0.76		0.78
SED	–	0.11	–	0.52	–	0.46	–	0.20	–	0.44	–	0.17	–	–
Gliricidia prunings (dry wt. t ha^{-1})														
5. Gliricidia/maize	–	–	1.85	1.43	0.98	2.21	1.22	0.41	1.77	2.17	1.12	2.48	0.85	1.27
6. Maize–maize (green-manured)	–	–	6.68	1.96	2.42	4.92	4.50	0.40	4.22	7.26	3.14	8.68	3.06	3.63
SED	–	–	0.36	0.08	0.16	0.16	0.29	0.09	0.09	0.30	0.14	0.49	0.23	–

[a] SR: short rains (mid-October–mid-February), LR: long rains (mid-March–July).

[b] Yields of grain legumes were averages per year of the respective systems and yields of gliricidia prunings were averages per season of the respective systems.

increased over the years in both the rotations in which cowpea was grown to as high as 80% incidence by the 1995 short rains.

3.3. Nutrients recycled

Maize in hedgerow intercropping (G/M) and biomass transfer system (MMG) received gliricidia prunings from one year (or two crop seasons) after the establishment of trees in these systems (Table 3). The prunings applied in different seasons varied enormously, and usually depended on rainfall in the preceding season and interval between harvests. The prunings incorporated in MMG were 2.2–3.7 times higher than in G/M (Table 3). However, the prunings harvested in both systems were similar in two very low rainfall seasons. On average, 1.27 t ha^{-1} of gliricidia prunings was added in hedgerow intercropping every season, which recycled 38 kg N and 3.4 kg P ha^{-1} to the topsoil (Table 4). The nutrients added through gliricidia prunings in the biomass transfer system were about three times higher than in hedgerow intercropping.

Cowpea and pigeonpea recycled small quantities of nutrients through litter in their respective cropping systems (CM, P/CM, P/M)(Table 4). The pigeonpea/cowpea intercrop recycled 30 kg N and 2.2 kg P ha^{-1} in the year of its cultivation. But as this system was grown only once in two years, the nutrients recycled on annual basis were 15 kg N and 1.1 kg P ha^{-1}. Thus, P/CM behaved similarly to CM, which recycled 13 kg N and 1.4 kg P ha^{-1} every year. The pigeonpea/maize intercrop had recycled 27 kg N and 1.6 kg P ha^{-1} per year. Among the annual legume-based systems, nutrient cycling through litter was highest in P/M as this system was grown every year.

3.4. Soil nutrients

All cropping systems influenced the soil nutrient status similarly and they caused a significant decline in soil organic C ($p < 0.05$), extractable P ($p < 0.01$) and exchangeable cations ($p < 0.01$) (Table 5). Although the reduction of soil organic C over the years was small (6–13% reduction) among different systems, the cowpea–maize rotation did not show any reduction.

The inorganic N in top 30-cm soil depth at the beginning of the 1995 short rains was significantly higher immediately after cowpea in the cowpea–maize rotation (i.e. system 2b) and continuous maize grown with gliricidia biomass than in continuous maize control (Table 6). All the legume-based systems recorded higher mineral N than the continuous sole maize in subsequent samplings after the crop was sown, but the status of mineral N decreased during the course

Table 4
Gliricidia prunings and litter of annual legumes incorporated into soil, and nutrients recycled in different cropping systems[a]

Cropping system	Prunings/litter (t ha^{-1} per season or per year)	Nutrient concentration (% dry matter)		Nutrients recycled/added (kg ha^{-1} per season or per year)	
		N	P	N	P
2. Maize–cowpea[b]	0.69	1.85	0.20	13	1.4
3. Maize–pigeonpea/cowpea[c]					
cowpea	0.44	1.85	0.20	8	0.9
pigeonpea	0.92	2.41	0.14	22	1.3
4. Pigeonpea/maize[d]	1.11	2.41	0.14	27	1.6
5. Gliricidia/maize[e]	1.27	3.02	0.22	38	3.4
6. Maize–maize[e] (green-manured)	3.63	3.02	0.22	114	8.6

[a] Results of hedgerow intercropping were based on 6.5 years from the 1989 short rains to the 1995 short rains and those of annual legume systems on 3 years from the 1992 long rains to the 1994 long rains.

[b] Nutrients recycled by cowpea per season, which was grown once every year in the system.

[c] Nutrients recycled by cowpea and pigeonpea per year, which were grown once every 2 years in this system.

[d] Nutrients recycled by pigeonpea per year, which was grown every year in this system.

[e] While nutrient addition through gliricidia prunings in hedgerow intercropping was due to nutrient recycling and biological nitrogen fixation within the system, the addition through green manuring was from outside the system.

Table 5
Soil nutrient changes in the 0−15 cm soil layer in different annual vs perennial legume-based cropping systems over a 5-year period at Machakos, Kenya

Cropping system	Soil C (%)		Extractable P (ppm)		Exchangeable cations ($cmol_c\ kg^{-1}$)					
					Ca		Mg		K	
	1	2	1	2	1	2	1	2	1	2
1. Maize−maize	1.28	1.11	13	10	6.8	5.2	2.1	1.4	0.77	0.39
2a. Cowpea−maize	1.25	1.25	21	15	6.9	5.8	2.3	1.5	0.77	0.46
2b. Maize−cowpea	1.34	1.25	19	14	7.2	6.1	2.5	1.7	0.87	0.46
3a. Pigeonpea/cowpea−maize	1.27	1.18	13	6	6.8	5.6	2.2	1.6	0.77	0.38
3b.Maize−pigeonpea/cowpea	1.30	1.14	16	9	7.0	5.7	2.2	1.6	0.73	0.44
4. Pigeonpea/maize	1.24	1.17	21	13	6.5	5.7	2.3	1.6	0.83	0.43
5. Gliricidia/maize	1.18	1.23	9	10	6.4	5.6	2.3	1.6	0.63	0.42
6. Maize–maize (green-manured)	1.25	1.18	14	12	6.6	5.7	2.1	1.6	0.77	0.64
Mean	1.26	1.16	16	11	6.8	5.6	2.2	1.6	0.75	0.45
SED[a] (systems)	0.07	–	5.0	–	0.39	–	0.11	–	0.07	–
SED (sampling years)	0.04	–	1.6	–	0.17	–	0.05	–	0.03	–
SED (years across systems)	0.12	–	4.8	–	0.51	–	0.16	–	0.08	–
SED (systems within years)	0.13	–	6.0	–	0.53	–	0.15	–	0.09	–

[a] Standard error of difference of means 1 = sampling in October 1989, 2 = sampling in August 1994.

of the season due to uptake by maize. Mineral N increased around the middle of the rainy season or remained similar to the beginning of the season under rotations and intercrop systems with pigeonpea. However, maize yields in this season did not show any significant relationship with inorganic N at any of the sampling dates because of limited rainfall.

Barrios et al. (1996a, b) reported earlier the SOM fractions and their rates of mineralisation in different systems of this trial measured in the 1993 long rains. As maize in that season failed, the effect of SOM fractions on maize yield could not be determined. However, maize yields in the previous 1992 short rains (y), when rainfall was adequate, were significantly related to N content in the light fraction SOM (x) ($y = 2.14 + 0.14x$, $r = 0.98$**). But in the subsequent 1993 short rains, when rainfall was inadequate from erratic distribution, maize yields were not influenced by the N content of the light fraction SOM.

3.5. *Economic returns*

Significant differences were noted among systems in terms of input costs primarily because of differences in labour requirement for field operations and costs of plant protection (Tables 1 and 7). The MMG

Table 6
Total inorganic nitrogen in 0–30 cm soil layer under different cropping systems during the 1995 short rains at Machakos, Kenya

Cropping system	Inorganic N (NO_3-N + NH_4-N) ($kg\ ha^{-1}$)				
	At crop sowing	14 DAS[a]	28 DAS	46 DAS	67 DAS
1. Maize−maize	21.6	26.1	31.7	20.4	10.0
2a. Cowpea−maize	32.0	36.7	45.8	51.9	53.3
2b. Maize−cowpea	66.2	63.4	89.3	35.4	19.1
3a. Pigeonpea/cowpea−maize	32.6	30.7	40.7	38.5	18.1
3b. Maize−pigeonpea/cowpea	45.9	43.3	64.1	39.9	17.1
4. Pigeonpea/maize	41.1	41.2	63.2	40.7	28.4
5. Gliricidia/maize	52.6	50.4	53.7	33.6	17.3
6. Maize−maize (green-manured)	155.4	110.7	100.2	79.5	82.9
SED[b]	15.9	4.7	4.7	4.8	4.1

[a] Days after crop sowing.
[b] Standard error of difference of means.

Table 7
Costs, labour requirement and net present value (NPV) of benefits of different annual and perennial legume-based cropping systems over a 6-year period (short rains 1989 to long rains 1995) at Machakos, Kenya

Cropping system	Total costs (US$)	Labour (days per year)	Net benefits (NPV, US$)	Return to labour (US$ per day)
1. Maize−maize	1367	234	2301	2.58
2. Cowpea−maize	1525	235	3026	3.09
3. Pigeonpea/cowpea−maize	1382	199	3417	3.80
4. Pigeonpea/maize	1150	160	3438	4.54
5. Gliricidia/maize	1637	257	1908	2.14
6. Maize−Maize (green-manured)	2797	343	1776	1.78
SED[a]	44	8	308	0.18

[a] Standard error of difference of means.

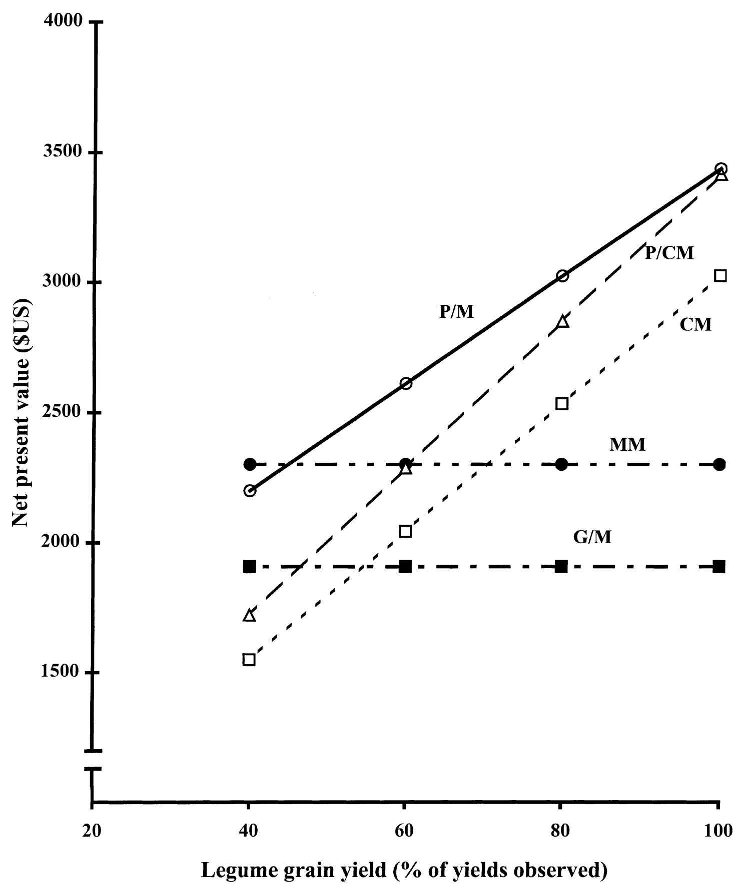

Fig. 2. Net present values of three grain legume-based cropping systems (P/M = pigeonpea/maize intercropping, P/CM = pigeonpea/ cowpea intercrop rotated with maize, CM = cowpea rotated with maize) estimated at different yield levels of legumes compared with those of hedgerow intercropping (G/M) and continuous double cropping of sole maize (MM).

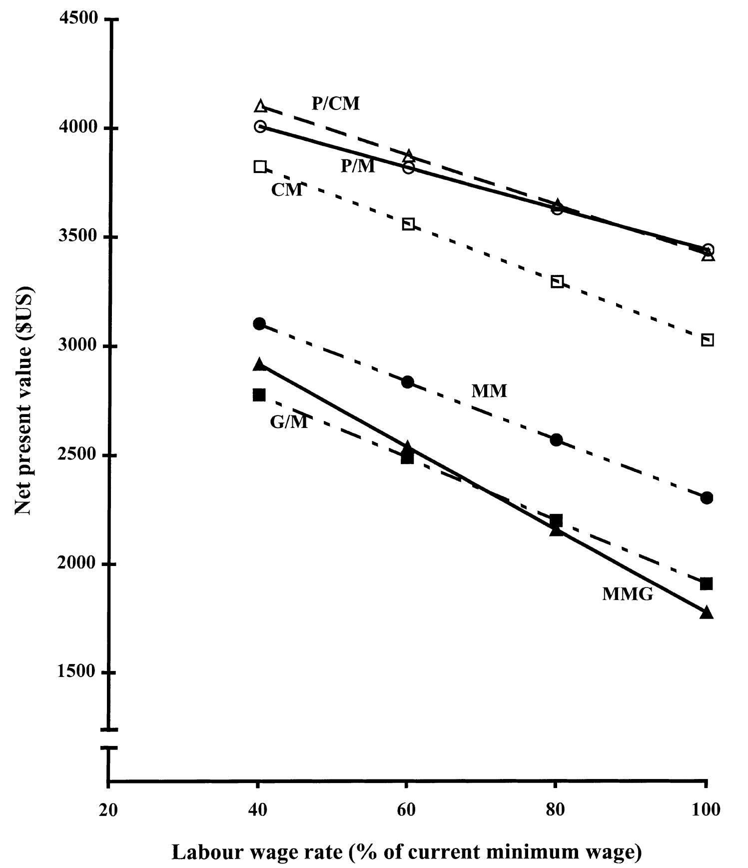

Fig. 3. Net present values of different cropping systems at different labour wage rates. (MM: continuous double cropping of maize, MMG: continuous double cropping of maize with gliricidia green-manure, CM: cowpea rotated with maize, P/CM: pigeonpea/cowpea intercrop rotated with maize, P/M: pigeonpea/maize intercrop, G/M: hedgerow intercropping).

system required on average 343 labour days per year compared with 234 for MM. Whereas maize rotated with cowpea (CP) required similar labour to MM, the crop rotated with pigeonpea/cowpea intercrop (P/CM) required 15% less labour and that intercropped with pigeonpea (P/M) needed 32% less labour than MM. The G/M required 10% higher labour than MM for managing hedgerows and incorporating prunings in the soil. The costs for protection of legumes against pests increased with the number of legumes in the system. The P/CM, in the year when legumes were grown, required on average US$ 107 for plant protection compared with only US$ 51 for the P/M. Between the two grain legumes, cowpea incurred higher costs than pigeonpea (US$ 64 versus 51 per crop) because of frequent and greater infestation by insect pests (Table 1). The pigeonpea/maize intercrop incurred the lowest costs at US$ 1150, followed by continuous sole maize and maize rotated with pigeonpea/cowpea intercrop, both of which incurred similar costs (Table 7). The biomass transfer system incurred 105% and hedgerow intercropping 20% higher costs than continuous sole maize.

The three grain legume-based systems (CM, P/CM, P/M) gave similar net benefits, which were significantly higher than those from continuous sole maize with or without gliricidia green-manure and hedgerow intercropping (Table 7). Net benefits from MMG were lowest at 77% and those from G/M were 83% of the benefits from MM. Returns to labour from

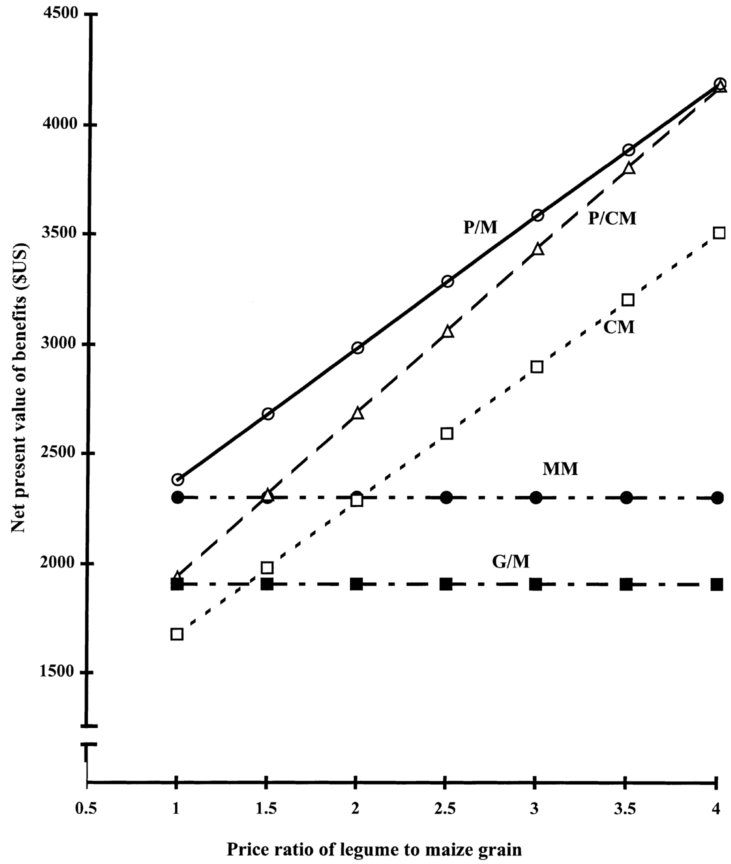

Fig. 4. Net present values of three grain legume-based (P/M: pigeonpea/maize intercropping, CM: cowpea and maize rotation, P/CM: pigeonpea/cowpea intercrop rotated with maize) and hedgerow intercropping (G/M) compared with continuous maize (MM) at different price ratios of legume to maize grain.

legume-based systems were 20–76% higher than those from MM. Return to labour was highest from P/M at US$ 4.54 per day, followed by P/CM at US$ 3.80 per day and CP at US$ 3.09. These returns per workday of labour were 1.8–2.7 times higher than the government fixed minimum wage. Although returns to labour from MMG and G/M were higher than the minimum wage, they were significantly lower than from MM.

The net benefits of annual legume systems depended very much on the grain yields of legumes (Fig. 2). If legume yields were lower than those observed in the study, for example at 80%, only the two pigeonpea-based systems (P/CM, P/M) gave substantially higher net benefits than both the continuous sole maize systems with or without green-manure. At 60% yields of legumes, only the P/M was more profitable than MM, and differences among other systems became small. If legume yields fall below 60%, then P/M was also not any more profitable than continuous maize (MM). The CM and P/CM systems were less profitable than MM if legume yields were lower than 60% of those observed in the study.

The government minimum wage used in the financial analysis here for agricultural labourers for the Machakos municipality is much higher than that generally paid by farmers. The labour wage in the rural areas is much lower than the minimum wage, and it varies within a season, but for simplicity a constant rate for the whole season was used. The superiority

of the grain legume-based systems over continuous maize did not change at different labour wages, except that the margin of profitability decreased slightly as the wage rates decreased (Fig. 3).

If legume grain prices were the same as maize, the legume-based systems, except the pigeonpea/maize intercrop, were less profitable than the continuous maize system (Fig. 4). The pigeonpea-based systems (P/M and P/CM) were more profitable than MM when legume grain was valued 1.5–2.0 times higher than maize grain, but the cowpea-based CM became attractive only when cowpea grain was valued 2.5 times higher than maize grain.

4. Discussion

Maize yield of 2 t ha^{-1} or more per season over 5 years of continuous double cropping in the control indicates that initially the experimental site was not nutrient-depleted unlike typical farmers' fields. The fairly high yields were also partly because of good agronomic management under researchers' control. However, nutrients became a limiting factor whenever rainfall was above normal or well distributed, as evident from significant maize response to green manuring in 5 out of 12 seasons. This maize response could be ascribed primarily to N in the gliricidia biomass as the site initially contained a high level of extractable P (average = 16 ± s.d. 4.3 ppm). In a parallel experiment on a nearby field that had five years of cropping history, maize yields were significantly increased by 40 kg N ha^{-1} in 6 out of 11 seasons (Mathuva et al., 1998). A significant linear relationship between yield and rainfall in most cropping systems and lack of any time-related trends in yields over years further indicate that maize yields in this study were influenced more by water than by soil fertility. The results point out that although nutrient depletion occurs slowly in the newly opened base-rich Alfisols in water-limited semi-arid tropics, N could become a limiting nutrient very soon and potential yields cannot be realised without external inputs. The decline of extractable P from the initial 16 to 11 ppm by the end of 6.5 years suggests that P inputs would be needed in due course.

Increased maize yield in grain legume-based systems in the presence of adequate water was the result of higher N availability to maize in those systems from the organic residues and residual effect of biological nitrogen fixed by the legumes ('legume effect') (Rego and Seeling, 1996; Giller et al., 1997). This was confirmed by the increased pool size of the active SOM and increased N mineralisation in those systems 4 years after the start of the trial (Barrios et al., 1996a, b). However, N was not limiting whenever rainfall was low or irregularly distributed. There might also be non-nitrogen benefits of legumes in rotation ('rotational effect') such as improved soil structure and water relations. Many previous studies have reported significant positive effects of grain legumes on yields of subsequent cereal crops as observed in this study (Kumar Rao et al., 1983; Lal et al., 1978; Giller et al., 1997). More frequent maize yield increases in rotation with cowpea than in pigeonpea-based systems could be ascribed to differences between these legumes in terms of nitrogen fixation, and quantity and quality of residues (leaf litter and roots) returned to the soil. As cowpea litter is of higher quality with low C : N and lignin + polyphenols : N ratios than pigeonpea litter (Mafongoya et al., 1998), it might have mineralized rapidly to make N available to maize. The mineral N status during the course of the season in pigeonpea systems confirms that pigeonpea residues mineralise slowly. In the biomass transfer system, the fresh and high quality gliricidia prunings decomposed rapidly to make N available to maize and increase its yield whenever water was not limiting (Mafongoya et al., 1998; Kang et al., 1990). However, maize yield increase only once in hedgerow intercropping was because of other factors than nitrogen.

The lack of a positive effect of hedgerow intercropping on maize yields even in seasons when N was clearly limiting, except when rainfall exceeded 500 mm, indicates that water was inadequate to meet the needs of both maize and hedgerows. Inadequate soil water limiting the response of alley crops to tree prunings in hedgerow intercropping in the semi-arid tropics has previously been reported (Rao et al., 1998). Roots of hedgerows managed as in this study were found to be concentrated in the top 0.5 m of the soil where crop roots are mostly confined, and consequently there is increased competition between hedgerows and alley crops for water (Govindarajan et al., 1996). Gliricidia was expected to be less competitive than other tree species adapted to semi-arid climates such as *Leucaeana leucocephala* and *Senna*

spectabilis because of its low root density in the crop root zone (Rao et al., 1998). The lack of improvement in maize yields over the 6.5-year period, even with gliricidia in this study, confirms that hedgerow intercropping with any woody perennial may not be appropriate to improve food crop production in the semi-arid tropics. Pruning of hedgerows to a low height (0.5 m) does not help to increase the alley crop yields, and may be counter-productive as it restricts the roots of hedgerows to the top soil and increases competition with crops for water (van Noordwijk et al., 1996), and reduces biomass production (Duguma et al., 1988).

Grain legumes usually command two to four times the price of maize and are marketed easily in most tropical countries, including Kenya. Such legume-based cropping systems should remain attractive under a wide range of situations. With markets generally being liberalised and opportunities for farmers to sell farm produce and buy household needs increasing, the emphasis can shift to income from simply producing staple food crops. Furthermore, as maize is more sensitive to drought than grain legumes, which occurs frequently in the semi-arid tropics, systems involving grain legumes are likely to be less risky and more attractive to farmers than continuous cultivation of maize. The pigeonpea-based systems were particularly more profitable because they required less labour for cultivation. As pigeonpea occupies both seasons of a year, it avoids labour for land preparation, sowing and weeding, and total crop failure in the event of poor rains in the second season, as had happened in the 1995 long rains. This indicates the low risk associated with pigeonpea-based systems in the highly variable climatic conditions of the semiarid tropics. In the Indian semi-arid tropics, intercropping systems of pigeonpea were found to be not only more profitable but also less risky than other annual crop systems (Rao and Singh, 1990).

How does feeding of tree biomass to livestock and returning manure to maize compare with direct use of biomass for green manuring? For farmers owning livestock, particularly in the peri-urban areas where opportunities for marketing of livestock products (e.g. milk) exist, hedgerow intercropping or a fodderbank with tree species that give high quality and palatable fodder such as leucaena would be more profitable than continuous sole maize (Mathuva et al., 1998). However, the same may not be possible with less palatable species such as gliricidia at many places (Simons and Stewart, 1994). Even for farmers who do not own cattle, the biomass transfer system is uneconomical because of extra labour needed for production, transporting to cropped plots and incorporation of biomass in the soil. Furthermore, smallholders may have limited opportunities to produce tree biomass for green manuring on their farms. Nevertheless, this technology might be relevant for high-value crops such as vegetables in small areas and where the opportunity costs for labour is low.

Increased wilt incidence on pigeonpea was because of its continuous cultivation in the same field, which was also the case in farmers' fields (Reddy et al., 1990). It appears that two seasons of break with maize can reduce wilt to some extent. However, the incidence of pests on both the grain legumes used in this study suggests the need for integrated pest management for realising the potential benefits of legumes.

The study leads to the conclusion that cropping systems based on grain legumes are more profitable, in terms of returns to land and labour, than continuous cropping of cereals with or without green manuring and hedgerow intercropping in semi-arid tropics. The choice between cowpea and pigeonpea is a matter of farmers' preference for home consumption, market prices and long-term rotational needs to avoid pests and diseases.

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